Properties of the Atlantic derived halocline waters over the Laptev Sea continental margin: Evidence from 2002 to 2009

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[1] A series of transects carried out in 2002–2009 across the Laptev Sea continental margin show consistent cross-slope differences of the lower halocline water (LHW). Over the slope the LHW core is on average warmer and saltier by 0.39°C and 0.26 practical salinity unit, respectively, relative to the off-slope LHW. Underlying Atlantic water (AW) thermohaline properties exhibit an opposite pattern; it is colder and fresher over the slope and warmer and saltier off the slope. Although on-slope and off-slope LHWs have different formation histories, our results suggest that an important part of the heat and salt lost from the AW is gained by the overlying LHW over the continental slope area. This implies the role of enhanced vertical mixing over the sloping topography, which contributes to the difference between the on- and off-slope LHW properties. The distribution of chemical tracers (dissolved oxygen and nutrients) provides further evidence supporting this interpretation and additionally suggests that the LHW may also be influenced by water from the outer shelf.

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1. Introduction

[2] The halocline layer (HL) of the Arctic Ocean Eurasian Basin represents a transition and critical buffer between the cold, fresher, surface mixed layer and the warm and saltier intermediate Atlantic water (AW) layer beneath, with the lower part of the HL, the low halocline water (LHW), occupying a salinity range of ~33 to 34.5 practical salinity unit (psu) [*Steele and Boyd*, 1998; *Rudels et al.*, 2004]. Generally, the HL is close to the freezing temperature and vertically stratified in salinity, and the associated density gradient suppresses the upward heat flux to the sea surface from the underlying AW. Given the recent increase of temperature in the AW layer over the Eurasian continental margin [*Polyakov et al.*, 2005; *Dmitrenko et al.*, 2008], understanding the formation, spreading, and modification of the overlaying LHW is important in predicting how the Arctic Ocean may respond to climate change.

[3] The LHW water over the Eurasian Basin is believed to be composed of a combination of (1) AW modified because of air cooling and sea-ice melting north and east of the Fram Strait and over the Barents Sea shelf [*Steele et al.*, 1995], (2) water originating from winter convection north of the Barents Sea [*Rudels et al.*, 1991, 1996], (3) water over the polynyas of the northern Kara and northwestern Laptev sea shelves [*Aagaard et al.*, 1981], and (4) water masses conditioned by a combination of all these mechanisms [*Rudels et al.*, 2004; *Rudels*, 2010]. There has been general agreement that the LHW over the Eurasian Basin is conditioned by advection from the northern Kara and Barents seas and adjacent Nansen Basin. Furthermore, *Rudels et al.* [2004] suggest that the LHW over the Eurasian continental slope of the Laptev Sea originates from the Barents Sea branch entering the Arctic Ocean through the St. Anna Trough (SAT), while the Fram Strait branch controls the LHW over the Nansen Basin. Expanding on the suggestion by *Rudels et al.* [2004], this paper focuses on the modification of the LHW over the continental slope of the Laptev Sea, with the aim of explaining the origin of the differences in the thermohaline properties between the on- and off-slope LHWs. In particular, we build on recent work by *Dmitrenko et al.* [2010], specifically looking at the effect of the enhanced vertical mixing between the LHW and underlying AW over the Laptev Sea continental slope.

2. Data and Methods

[4] We use data from a cross-slope transect along 126°E (Figure 1 inset and Figure 2) gathered during 2002–2009 Nansen and Amundsen Basins Observational System (NABOS) cruises in August–October. A shipboard SBE19 + CTD (conductivity-temperature-depth) was used to record conductivity,

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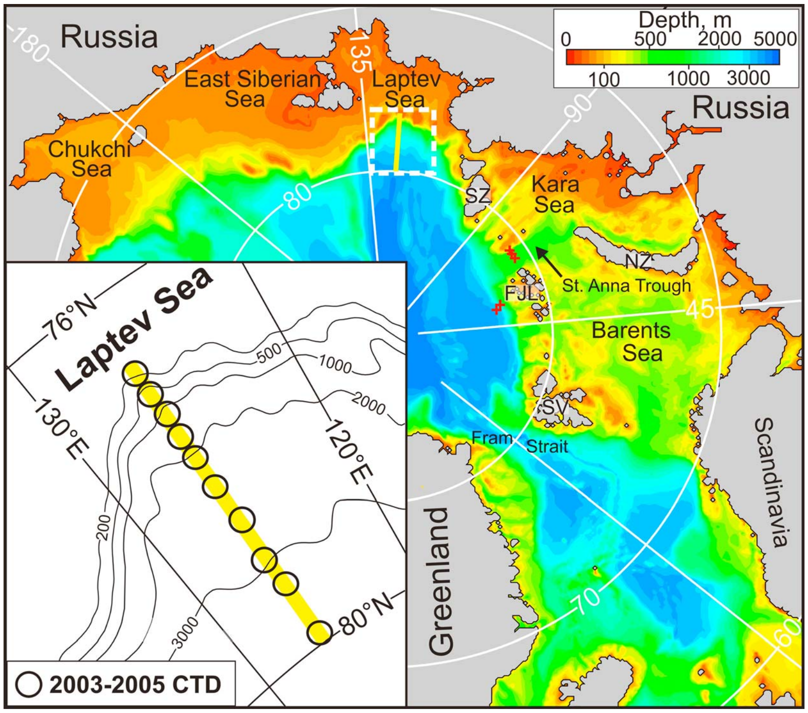

Figure 1. Map of the Arctic Ocean. Red crosses show positions of stations occupied in 1996 across the eastern slope of the St. Anna Trough and in 2009 north of Franz Josef Land (FJL). The yellow line (white dashed square) shows a CTD section occupied during the 2002–2009 NABOS cruises. Inset is an enlarged view of this section. The CTD stations taken in 2003–2005 are shown for reference purposes. Bathymetry is adapted from the International Bathymetric Chart of the Arctic Ocean (IBCAO), 2001 version.

temperature, and depth vertically every 15–20 cm. Seawater for dissolved oxygen (DO) and nutrient analysis was sampled using a 24-bottle rosette sampler in 2007–2009. All technical details on the methods and accuracy of CTD and chemical measurements can be found in the cruise technical reports (http://nabos.iarc.uaf.edu/cruise/reports.php). We also use bottom layer (30–50 m depth) temperature and salinity data obtained in September 2007 and 2008 during Russian-German TRANSDRIFT expeditions. Measurements were done using a shipboard SBE19 + CTD. Data were collected southward of the cross-slope transect (between meridians 120°E and 130°E). There were 91 CTD profiles used to derive the 2007–2008 mean bottom layer temperature and salinity.

[5] The LHW is characterized by a temperature minimum with the temperature-salinity (TS) curve generally close to the freezing line [*Rudels et al.*, 2004]. On a TS diagram, the LHW can usually be identified by a bend or kink close to the freezing point [*Aagaard et al.*, 1981; *Rudels et al.*, 2004; *Rudels*, 2010]. However, data from stations on-slope often exhibit no kink in TS diagrams (Figures 3a and 3b), which prevents us from defining the on-slope LHW by TS kink. The on-slope profiles with no kink tracing LHW have been also reported by other authors [*Rudels*, 2010; *Woodgate et al.*, 2001]. For the on-slope region west of Franz Josef Land (FJL), *Rudels* [2010] has explained this pattern by enhanced vertical mixing with the underlying AW layer.

[6] In this paper, we examine LHW properties for selected on-slope (<2000 m) and off-slope (>2000 m) CTD stations within the depth range of the off-slope temperature minimum (see Figures 1 and 2 for station locations). In situ temperature is used throughout the analysis. For all off-slope stations from a particular year, the mean depth, temperature, and salinity were computed for the 5 m thick water layer with the LHW minimum temperature; this, though, was restricted to a salinity range of 33.2–34.3 psu. These were then compared with the properties of the on-slope LHW, derived for the same depth range as that of the off-slope LHW temperature minimum. Our approach for comparing LHW properties within the average depth of the off-slope temperature minimum is preferred over other potential methods such as analyzing the data along the LHW density range, because vertical mixing modifies both temperature and salinity (density). For the depth range of the off-slope temperature minimum, we analyze both cross-slope temperature and salinity (density) differences. In contrast, for the density range of the off-slope temperature minimum, only the temperature difference is significant, but the salinity difference is negligible (within the LHW range of temperatures and salinities, the density is mainly driven by salinity). We note, however, that horizontal advection of LHW along isopycnals could play a role in shaping the cross-slope difference in LHW temperature and salinity, but the present analysis does not permit this feature to be resolved.

[7] The off-slope LHW salinity exhibits a positive trend, gradually increasing from 33.28 ± 0.32 psu in 2003 to 34.09 ± 0.07 psu in 2009. Therefore, the off-slope and on-slope LHW characteristics were averaged over the entire period of observations (2002–2009) and for the time periods 2002–2005 and 2006–2009 separately (Table 1). The

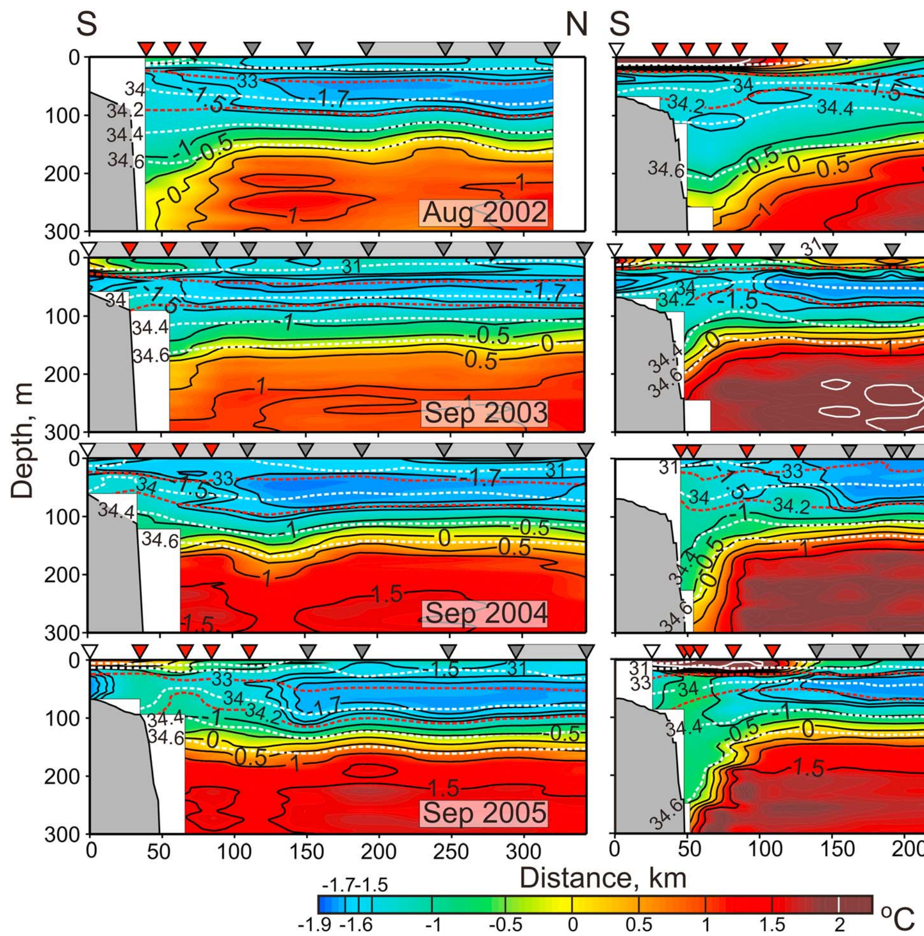

Figure 2. 1 m binned sections of in situ temperature (°C) and salinity (psu) taken in August–October 2002–2009 across the continental slope of the central Laptev Sea following ~126°E, adapted from the work of *Dmitrenko et al.* [2010]. Black solid lines and white and red dashed lines depict temperature and salinity contours, respectively. The LHW is roughly located between salinity contours 33 and 34.2, shown by red dashed lines. Arrows on the top show the CTD stations. Red arrows identify stations nearest to the continental shelf over depths between 80 and 2000 m (shown in Figure 3 by red lines). Gray arrows identify stations occupied off-slope and typically deeper than 2000 m (shown by gray lines in Figure 3). White arrows depict stations shallower than 80 m (not shown in Figure 3). Blank areas represent missing data. Gray shading on the top shows sea-ice cover with an ice concentration of >50%.

underlying AW core traced at the depth of the off-slope temperature maximum was analyzed the same way.

3. Results

[8] Throughout the entire period of observations (2002–2009), the LHW cross-slope section properties exhibit similar on-slope and off-slope patterns, with warmer and saltier LHW on-slope and cooler and less saline water off-slope (Figure 2). In the 2002–2009 mean, the off-slope LHW core is centered at 51 ± 7 m, with salinity and temperature values of $S = 33.70 \pm 0.31$ psu and $T = -1.77$°C ± 0.03°C, respectively (Table 1). In contrast, over the same depth range the on-slope LHW properties are $S = 33.96 \pm 0.14$ psu and $T = -1.38$°C ± 0.16°C (Table 1 and Figures 3a and 3b). The underlying AW exhibits an opposite pattern. The AW core centered at 246 ± 12 m is warmer and saltier off-slope (T = 1.62°C ± 0.33°C, S = 34.88 ± 0.02 psu) and cooler and fresher on-slope (T = 1.06°C ± 0.59°C, S = 34.81 ± 0.06 psu). These characteristic patterns are in agreement with CTD data of cross-slope sections occupied in 1995 along 105°E [*Rudels et al.*, 2000] and in 1993 along 118°E [*Woodgate et al.*, 2001], which show similar features of the LHW and AW. Figures 3c and 3d and Table 1 also illustrate off-slope LHW mean salinity differences between the two periods, shifting from 33.44 ± 0.15 psu in 2002–2005 to 33.95 ± 0.17 psu in 2006–2009 within the depth range (~45–55 m) of the temperature minimum. Furthermore, the LHW is denser on-slope (~0.2 kg m^{-3}), and the upper boundary of the AW layer (from ~120 to 250–300 m) is less dense (~0.1 kg m^{-3}) relative to the off-slope (Figure 4).

[9] The temperature difference between the off-slope and on-slope LHW is statistically significant (based on Student's *t* distribution at the 90% confidence level) for the entire period of our cross-slope observations (Figures 3a and 3b). In contrast, the salinity difference appears to fall below the level

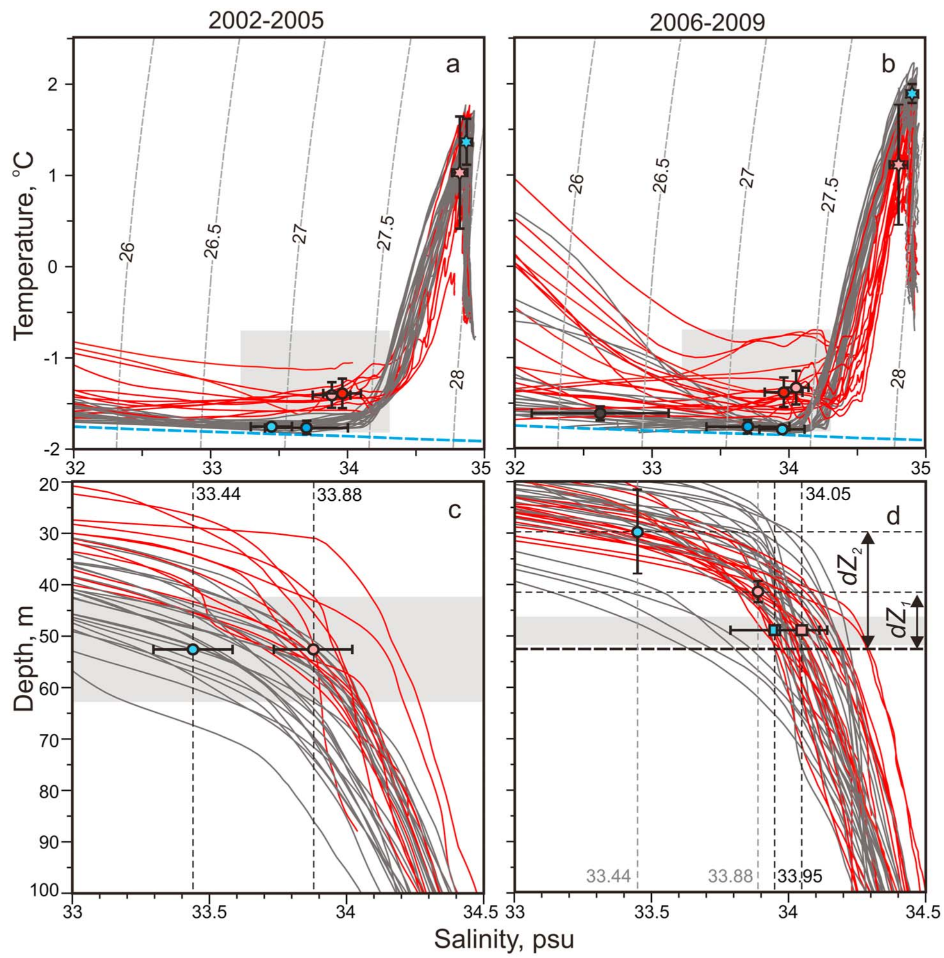

Figure 3. Water properties for the cross-slope section along 126°E. In situ temperature and salinity curves for (a) 2002–2005 and (b) 2006–2009. The area marked by gray shading indicates the approximate properties of the halocline layer. Red curves are the on-slope stations in water depths between 80 and 2000 m, showing the warmer LHWs. Gray curves are the deeper off-slope stations, with LHW near the freezing point (for station positions, see Figures 1 and 2). Pink and blue barred dots and stars show the mean TS characteristics ± one standard deviation for a, 2002–2005 and b, 2006–2009 for the on-slope and off-slope stations, respectively (dots for the core of the LHW and stars for the AW). In Figures 3a and 3b, the red and deep blue barred dots show the 2002–2009 mean ± one standard deviation. In Figure 3b, the black barred dot shows the 2007–2008 mean bottom water (30–50 m depth) temperature and salinity ± one standard deviation over the shelf area (120°E–130°E) south of the cross-slope transect. Dashed gray lines are sigma-0 isopycnals in kg m^{-3}. The dashed blue line is surface freezing temperature. (c, d) Vertical salinity profiles for the approximate depth and salinity ranges of the halocline layer. In 3c, the blue and pink barred dots show 2002–2005 mean salinities of the LHW ± one standard deviation for the off-slope and on-slope stations, respectively. In 3d, the blue and pink barred squares show 2006–2009 mean salinities of the LHW ± one standard deviation for the off-slope and on-slope stations, respectively. Mean depths associated with 2002–2005 off-slope and on-slope salinity ± one standard deviation are shown by blue and pink barred dots, respectively. The gray shading shows the mean depths for the cold core of the LHW off-slope for c, 2002–2005 and d, 2006–2009 following Table 1.

Table 1. Thermohaline Characteristics for the On-Slope and Off-Slope LHW and AW Cores

	On-Slope				Off-Slope					
	"Warm" LHW		"Cold" AW		"Cold" LHW			"Warm" AW		
Years	*T* (°C)	*S* (psu)	*T* (°C)	*S* (psu)	*D* (m)	*T* (°C)	*S* (psu)	*D* (m)	*T* (°C)	*S* (psu)
2002–2009	−1.38 ± 0.16	33.96 ± 0.14	1.06 ± 0.59	34.81 ± 0.06	51 ± 7	−1.77 ± 0.03	33.70 ± 0.31	246 ± 12	1.62 ± 0.33	34.88 ± 0.02
2002–2005	−1.42 ± 0.14	33.88 ± 0.14	1.02 ± 0.61	34.82 ± 0.05	53 ± 11	−1.75 ± 0.02	33.44 ± 0.15	249 ± 7	1.36 ± 0.25	34.86 ± 0.02
2006–2009	−1.33 ± 0.18	34.05 ± 0.09	1.11 ± 0.66	34.80 ± 0.07	49 ± 3	−1.79 ± 0.02	33.95 ± 0.17	243 ± 16	1.89 ± 0.10	34.90 ± 0.01

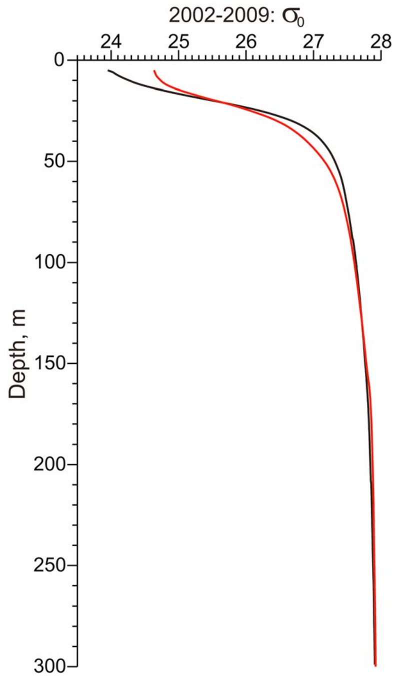

Figure 4. Mean (2002–2009) vertical sigma-0 profiles for (red) on-slope and (black) off-slope stations.

of significance (Figures 3a, 3b, and 3d). We argue that this discrepancy is entirely attributed to a combination of (1) cross-slope difference of AW properties mainly influenced by the AW boundary current shifted off-slope (Figure 2) and (2) warming and salinification of the AW boundary current in 2006–2009 relative to 2002–2005 (compare AW core mean temperatures and salinities for 2002–2005 and 2006–2009 in Table 1 and Figures 3a and 3b). From historical oceanographic data and 1584 CTD profiles acquired in the Eurasian Basin in 2007, *Polyakov et al.* [2010] concluded that the recent AW warming has been associated with a shoaling of the upper AW boundary and weakening of the Eurasian Basin stratification. Our results from the Laptev Sea continental slope are consistent with this assessment. Following AW warming and salinification, the depth of isohaline 33.44 psu, which marks the core of the off-slope LHW in 2002–2005 (Table 1), was uplifted by 22 m in 2006–2009 (dZ_2 in Figure 3d). On-slope, however, these changes were much less, and the isohaline 33.88 psu, roughly marking the on-slope LHW core in 2002–2005 (Table 1), was elevated only by 11 m in 2006–2009 (dZ_1 in Figure 3d). Based on the mean (2002–2009) off-slope and on-slope salinity profiles (not shown), these vertical displacements correspond to positive salinity anomalies of ~1.2 psu and 0.3 psu that arise in 2006–2009 for the off-slope and on-slope LHWs, respectively. Hence, changes imposed by AW modification in 2006–2009 substantially disrupted the statistical significance of the salinity difference between the off-slope and on-slope LHW, as evident from Figure 3d.

[10] Although at a coarser resolution relative to CTD measurements, the distributions of hydrochemical variables in 2007–2009 reveal consistent patterns of the on-slope and off-slope LHWs in 2007–2009. The characteristic feature in the on-slope LHW is the presence of a local DO minimum and enhanced silicate (Si) concentrations (Figure 5). This feature is also traceable within the underlying upper AW down to depths of ~200 m (Figures 5 and 6). DO saturations in the on-slope LHW are 2%–8% lower than in the off-slope LHW, where saturations vary between 86% and 92% (Figures 5a and 6, left-hand sides). The silicate concentration in the on-slope LHW is relatively high (4.5–7.0 μmol kg^{-1}). In contrast, the off-slope LHW is characterized by low Si (~2–3 μmol kg^{-1}, Figures 5b and 6, right-hand sides). There is also an associated on-slope elevated mean nitrate

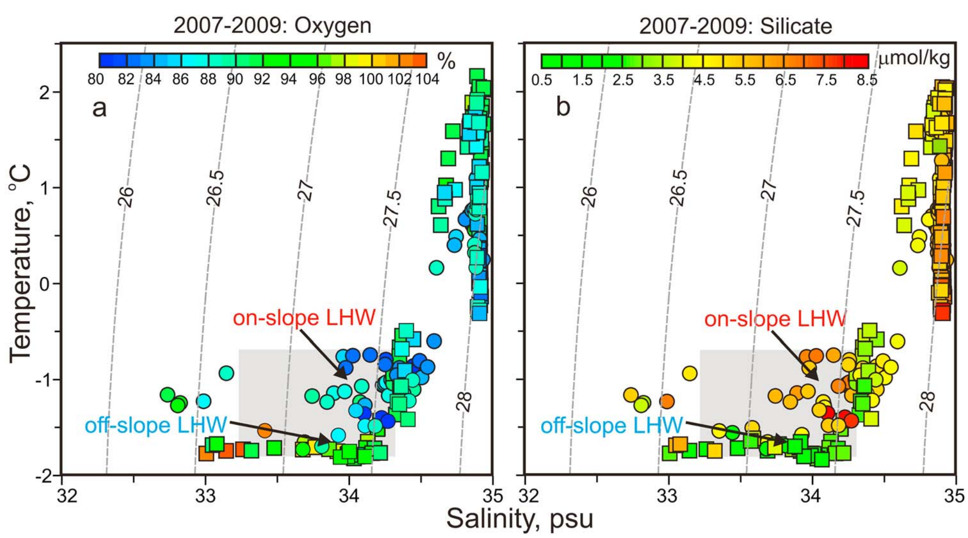

Figure 5. TS scatterplots for 2007–2009 chemical data, with color bars indicating (a) oxygen saturation (%) and (b) silicate concentration (μmol kg^{-1}) values as per color scale. Dots and squares depict the on-slope and off-slope stations, respectively. The area marked by gray shading indicates the approximate properties of the halocline layer as in Figures 3a and 3b. Dashed gray lines are sigma-0 isopycnals in kg m^{-3}.

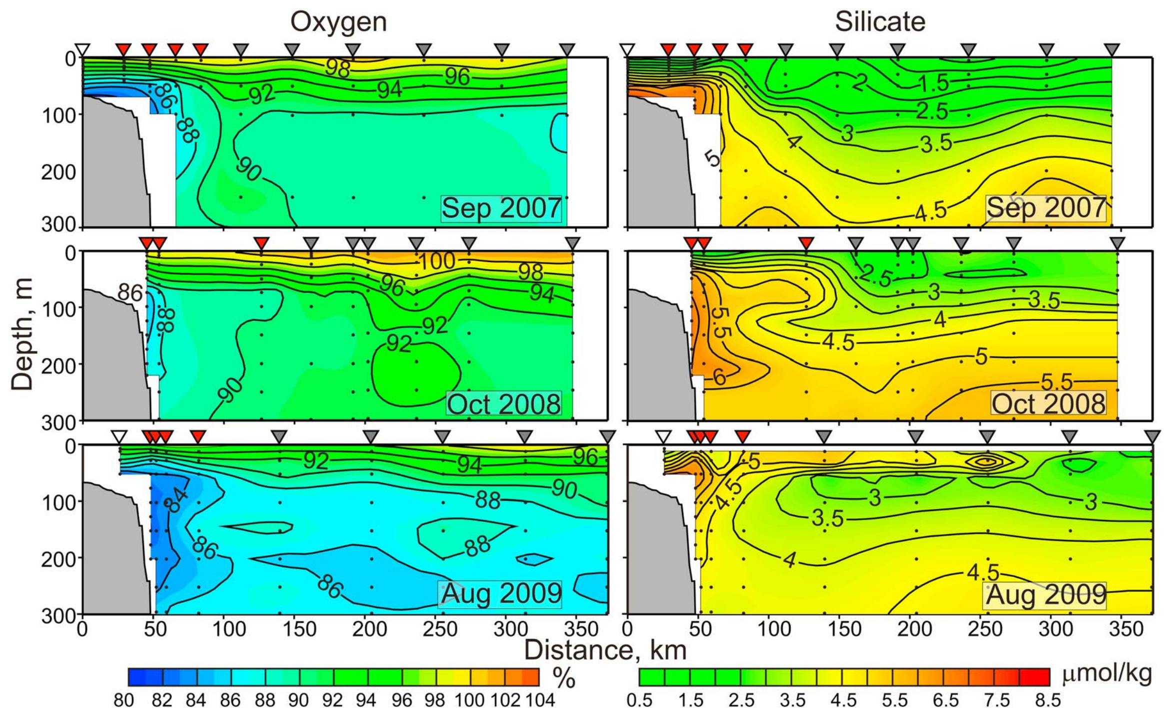

Figure 6. (left) Oxygen saturation (%) and (right) silicate (μmol kg^{-1}) along the cross-slope section taken in August–October 2007–2009 across the central Laptev Sea continental slope following ~126°E. Dots mark the water sampling levels.

concentration of 7.2 μmol kg^{-1}, while the off-slope LHW mean nitrate concentration is 6.9 μmol kg^{-1} (not shown).

4. Discussion

4.1. Upstream Source of the LHW

[11] *Rudels et al.* [2004] concluded that "the Barents Sea branch halocline is distinguished from the Fram Strait branch halocline by higher salinities and higher temperatures that result from the stronger vertical mixing with warmer Atlantic water occurring at the continental slope." Furthermore, *Rudels* [2010] suggested that the halocline water derived from the Barents Sea branch is more saline because of interaction with AW in the Barents and Kara seas. This can favor stronger downstream mixing with underlying AW that is due to the resulting decrease in salinity (density) vertical stratification. However, it is still unclear whether differences in temperature and salinity of the two halocline branches originate from differences in the source waters properties, are due to different formation mechanisms, or are caused by on-slope modification of the LHW as it flows along the Nansen Basin continental slope.

[12] For example, CTD profiles taken in 1996 across the Barents Seawater inflowing from the Arctic Ocean at the eastern slope of the SAT (see Figure 1 for station positions) show the LHW over a depth/density range that is similar to that of the on-slope LHW in the Laptev Sea. However, the LHW in the SAT is close to the freezing temperature (Figure 7a). This suggests no direct linkage between the LHW in the Barents Sea and the on-slope LHW in the Laptev Sea that actually shows a fairly consistent positive temperature anomaly relative to the freezing temperature. In contrast to those at the SAT, CTD profiles taken in 2009 north of FJL reveal thermohaline patterns for the LHW that are entirely consistent with those for the central Laptev Sea, with warmer and saltier on-slope LHW and cooler and fresher off-slope LHW (Figure 7b). However, given the unknown seasonal and interannual variability, the result of the interaction between these two halocline branches at their confluence in the northern Kara Sea is highly uncertain. We acknowledge that CTD profiles shown in Figure 7 are only a snapshot, and from them we cannot elaborate on eliminating the Barents Sea and/or Fram Strait branch as the potential source(s) of the downstream on-slope LHW anomaly.

[13] The existing view on the upstream LHW source regions by *Aagaard et al.* [1981], *Steele et al.* [1995], and *Rudels et al.* [1996, 2004], implies that the Barents Sea branch halocline could potentially feed both the on- and off-slope LHWs downstream in the Laptev Sea; however, the formation of each branch may be due to different mechanisms. That is, if the LHW is formed upstream by winter convection, then the water at the bottom of the LHW would be expected to have near-freezing temperatures, since brine rejection on freezing drives convection ("convective halocline"; e.g., *Woodgate et al.*, 2001). AW modification that is due to sea-ice melting and/or river runoff over the Barents and Kara seas does not necessarily result in halocline waters with freezing temperatures ("advective halocline"; e.g., *Woodgate et al.*, 2001).

[14] Thus, given the temperature characteristics of the off-slope and on-slope LHWs, we can conclude that the off-slope LHW properties are consistent with an upstream convective halocline, while the on-slope LHW characteristics are consistent with an upstream advective halocline

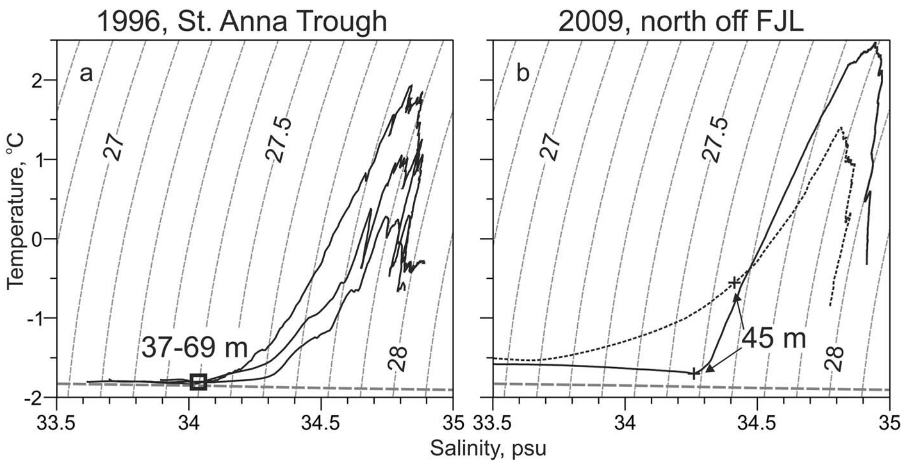

Figure 7. In situ temperature and salinity curves (Figure 7a) in the northern Kara Sea, August 1996, and (Figure 7b) north of FJL, August 2009. (a) Black lines show CTD profiles taken at the eastern slope of the St. Anna Trough across the Barents Sea water inflowing the Arctic Ocean, stations from expedition ARKXII, R/V *Polarstern*. (b) Black dashed line shows the on-slope profile KD1409 (82°29.8′N, 60°00.2′E), and the black solid line shows the off-slope profile KD1709 (83°10.4′N, 60°00.7′E), stations from expedition NABOS 2009, IB *Kapitan Dranitsyn*. The square depicts a LHW temperature minimum at 37–69 m. The cross marks the depth for the off-slope LHW temperature minimum at 45 m. Dashed gray lines are sigma-0 isopycnals in kg m^{-3}. The dashed thick gray line shows surface freezing temperatures.

(Table 1 and Figures 3 and 7). The question still remains however: How can the on-slope warmer LHW, having a source area as far away as ~1000 km upstream of our observational site (Figure 1), consistently maintain a positive temperature anomaly? If downstream vertical mixing associated with sea-ice formation for instance, were to be considered, the east Severnaya Zemlya (SZ) coastal polynya overlying the Laptev Sea continental slope off the SZ Archipelago (Figure 1) could potentially create cold waters dense enough to ventilate water layers down to the depth of ~400 m [*Ivanov and Golovin*, 2007], but this is not observed in this paper. Thus, given this consideration, the local (on-slope) modification of the LHW is a likely explanation for the difference between the on- and off-slope LHW properties.

4.2. Local Modification of the LHW

[15] In this section we argue that our records suggest that an important proportion of heat, salt, and mass lost from the AW are gained by the overlying LHW over the continental slope area, thus explaining a significant portion of the difference between the on- and off-slope LHW properties. We estimate the heat contents of the LHW and underlying upper AW to assess the efficiency of the upward heat loss over the continental slope on the way from the hypothetical confluence of the two halocline branches (north of the SAT, ~75°E) to the central Laptev Sea (126°E). For these estimates the off-slope conditions at 126°E are chosen as initial conditions, and the properties of the AW and LHW on-slope and off-slope are assumed to be the same at the initial point. Following this assumption, we neglect along-slope changes in the AW including any mixing and cross-slope changes caused by the topographically controlled off-slope shift of the AW boundary current jet. We note that heat loss estimates based on this assumption are only instructive and are likely to be biased toward the lower bound. They are made to illustrate the importance of on-slope LHW thermohaline anomalies in terms of heat exchange. Because of insufficiently understood interactions between the Fram Strait and Barents Sea branches of halocline at their confluence in the northern Kara Sea (e.g., Figures 3 and 7), any other assumptions about the upstream differences between on-slope and off-slope LHW properties would be highly uncertain.

[16] The LHW was defined to lie between the off-slope temperature minimum (~50 m) and the intersection point of the on-slope and off-slope temperature profiles (versus potential density) at ~110 m. The underlying upper AW layer was defined as extending down to the mean depth of the AW core temperature maximum (~250 m). We obtain that the mean (2002–2009) on-slope LHW layer heat content increases by 48 ± 34 MJ m^{-2} on reaching 126°E, while the on-slope upper AW layer heat content decreases by 400 ± 280 MJ m^{-2}. This suggests that 2% to 68% of the heat lost by the AW over the continental slope can be gained by the overlaying LHW. Thus, an important amount of the AW heat loss between the SAT and the central Laptev Sea may be attributed to strong vertical mixing over the continental slope and associated rough topography, as suggested by several previous observational and modeling studies (e.g., *Holloway and Proshutinsky* [2007]; *Sirevaag and Fer* [2009] and references therein).

[17] Having assessed the efficiency of the upward heat loss over the continental slope, we now discuss two processes potentially responsible for the observed on-slope LHW anomalies: double-diffusive (DD) mixing and turbulent mixing. The vertical thermohaline structure beneath the LHW is favorable for diffusive layering, which is characterized by the different diapycnal diffusivities for heat and salt, depending on the density ratio [e.g., *Rudels et al.*, 1991]. DD mixing gives a negative upward buoyancy flux that results in enhanced stratification and a decrease in

potential energy. In contrast, turbulent mixing works the opposite way, decreasing stratification and increasing the potential energy of the water column. The vertical density profiles in Figure 4 suggest that the potential energy of the on-slope water column is higher than that of the off-slope. Overall, this means that DD convection fluxes cannot explain the cross-slope differences in the LHW, which is more likely due to more efficient turbulent mixing on-slope. From snapshot velocity and CTD profiles taken over the central Laptev Sea and the adjoining Arctic Ocean in 1993, *Dewey at al*. [1999] reported enhanced vertical heat flux over the slope, exceeding vertical heat flux in the deep regions by an estimated factor of up to 3. They suggested that this diffusion is associated with elevated tidal forcing over the shelf break and slope regions. From CTD profiles taken over the same region in 2007, *Polyakov et al.* [2010] estimated the vertical heat flux over the slope to be twice more efficient than that for the adjoining Eurasian Basin. Microstructure observations in October 2008 also show enhanced turbulent dissipation and mixing over the Laptev Sea continental shelf break, with 12 h average upward heat fluxes of ~12 W m^{-2} [*Lenn et al.*, 2011] that are considerably larger than the AW boundary current values of ~1 W m^{-2} farther north [*Lenn et al.*, 2009]. It is also in general agreement with conclusions by *Sundfjord et al.* [2007] and *Sirevaag and Fer* [2009] that the Arctic turbulent mixing may still be important along the boundaries and steep bottom topography. While a number of TS profiles in Figure 3 exhibit no direct mixing lines between the LHW and AW, we suggest that the clear signature of vertical mixing could be masked by other potentially contributing processes such as the interannual variability in the cross-slope shift of the AW boundary current jet, AW advection, and/or the lateral exchange of the AW jet with ambient on-slope water. In support of these suggestions, in section 3 we have demonstrated how the inflow of saltier AW alters the off-slope LHW properties, masking the clear signature of vertical mixing over the continental slope.

[18] The distribution of hydrochemical variables provides further evidence supporting vertical mixing as an important process contributing to the local modification of the on-slope LHW. Our 2007 data from the shelf (not shown) reveal low DO concentrations and elevated nutrient concentrations over the midshelf to the shelf-break region (from about 30 to 100 m depth), which likely result from the oxidation of organic matter, silica dissolution, and efflux of nutrients from the sediments. This is also in agreement with data from the Laptev Sea shelf reported by *Nitishinsky et al.* [2007]. *Jones and Anderson* [1986] also associated the nutrient maximum and DO minimum in the Arctic Ocean water of salinity 33.1, with water from the Arctic continental shelves. Recently, from reduced NO values (NO is a quasi-conservative property defined by *Broecker*, 1974, as the sum of the oxygen concentration and nine times nitrate concentration), *Alkire et al.* [2010] suggested a direct shelf influence (most likely from Siberian shelves) to the LHW in the central Arctic Ocean. It is possible that an admixture of Laptev Sea shelf bottom water provides a source of the nutrient-enriched and oxygen-depleted signature observed in the on-slope LHW. For this to occur, wind-driven transport of the LHW onto the shelf, mixing with shelf water, and the return of the LHW would need to be invoked [*Woodgate et al.*, 2005]. In this manner, the on-slope LHW acquires the observed signature (low DO, high Si). Once the wind transport has ceased, the LHW moves back onto the slope, where vertical mixing is expected and the signal is transferred to the upper bound of the AW, having an effect down to an ~200 m depth. The silicate values for the on-slope LHW exceed those for the off-slope LHW by a factor of 2, while a difference in nitrate concentrations is only ~10%. This indicates no direct coupling between these two water masses, and it can also point to the evolvement of a denitrification (utilization of nitrates for organic matter oxidation; see *Chang and Devol*, 2009), on-slope, stipulating characteristic chemical signature in the on-slope LHW. Further evidence from stable oxygen isotopes analysis suggests a contribution from shelf waters, but also indicates that on-slope vertical mixing must contribute to the isotope signature of LHW at the Laptev Sea continental shelf as well (D. Bauch et al., manuscript in preparation, 2011).

[19] In support of the mechanism proposed, *Dmitrenko et al.* [2010] revealed warmer and saltier LHW from the Laptev Sea continental slope over the Laptev Sea outer shelf, at depths between 50 and 100 m. They showed a positive correlation between the outer shelf bottom temperature and (1) the AW boundary current core temperature and (2) the local zonal wind. This result is consistent with on-shelf wind-driven incursions of the LHW warmed up over the slope by vertical exchange with the underlying AW [*Dmitrenko et al.*, 2010]. Complementing the results by *Dmitrenko et al.* [2010], the present study shows that mixing between the off-slope LHW and shelf bottom water at positions southward of our cross-slope transect (from 30 to 50 m, $S = 32.62 \pm 0.50$, $T = -1.61°C \pm 0.06°C$) alone would make the off-slope LHW less salty (by ~0.6 psu) and just a little warmer (within 0.2°C) (Figure 3b). This is not evident in our data, which show saltier and warmer on-slope LHW relative to the expected mixture between the off-slope LHW and midshelf water (Figure 3b). Figure 3b also eliminates the midshelf as a possible source of the on-slope LHW over the Laptev Sea continental margin. The 2007–2008 midshelf water is not dense enough to supply the on-slope LHW (Figure 3b).

5. Conclusions

[20] Our results show that consistent differences exist in the cross-slope characteristics of the LHW over the Laptev Sea continental slope, with warmer and saline on-slope LHW and cooler and fresher off-slope LHW. The upper AW layer exhibits the opposite pattern in temperatures and salinities; it is fresher and colder on-slope and warmer and more saline off-slope. The water column over the slope is less stratified than in the interior of the basin: At the slope, the upper part is denser, while the deeper part is less dense relative to the basin interior at similar depths. This indicates that the heat, salt, and mass lost from the AW are partly gained by the overlying LHW. The distributions of chemical tracers (DO and nutrients) are consistent with local on-slope and outer shelf modifications of the LHW. Enhanced on-slope vertical mixing is hypothesized to account for an important proportion of the difference between the on- and off-slope LHW properties. The effect other mechanisms may have on the on-slope vertical mixing cannot be fully discriminated with our analysis. For example, we are assuming

a common origin for the on- and off-slope LHWs, and further research is thus needed to assess the contribution of upstream regions to the formation of the on-slope LHW anomalies. While further studies are necessary to establish the forcing for this process, our analysis shows that the modification of the Arctic halocline is most apparent near the continental slope and strongly implies the influence of enhanced vertical mixing over the sloping topography.

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